

Neutron-proton bremsstrahlung from intermediate energy heavy-ion reactions as a probe of the nuclear symmetry energy?

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Hard photons from neutron-proton bremsstrahlung in intermediate energy heavy-ion reactions are examined as a potential probe of the nuclear symmetry energy within a transport model. Effects of the symmetry energy on the yields and spectra of hard photons are found to be generally smaller than those due to the currently existing uncertainties of both the in-medium nucleon-nucleon cross sections and the photon production probability in the elementary process $pn \rightarrow pn\gamma$. Very interestingly, nevertheless, the ratio of hard photon spectra $R_{1/2}(\gamma)$ from two reactions using isotopes of the same element is not only approximately independent of these uncertainties but also quite sensitive to the symmetry energy. For the head-on reactions of $^{132}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$ at $E_{\text{beam}}/A = 50$ MeV, for example, the $R_{1/2}(\gamma)$ displays a rise up to 15% when the symmetry energy is reduced by about 20% at $\rho = 1.3\rho_0$ which is the maximum density reached in these reactions.

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The density dependence of the nuclear symmetry energy $E_{\text{sym}}(\rho)$ is important for understanding many interesting questions in both nuclear physics and astrophysics[1, 2]. In particular, the reaction dynamics and many observables of heavy-ion reactions are strongly influenced directly by the corresponding nuclear symmetry potential[3, 4, 5]. In turn, these observables can be used as effective probes of the symmetry energy $E_{\text{sym}}(\rho)$. Indeed, considerable progress has been made recently in constraining the $E_{\text{sym}}(\rho)$ at sub-normal densities using heavy-ion reactions[6, 7, 8, 9]. However, the behavior of the nuclear symmetry energy at supranormal densities remains rather illusive. A quick review of the current situation of the field[10] reveals that essentially all known probes of the $E_{\text{sym}}(\rho)$ in heavy-ion reactions are hadronic in nature. These probes, especially if used for studying the high density behavior of the $E_{\text{sym}}(\rho)$, inevitably suffer from distortions due to the strong interactions in the final state. Although selections of some especially delicate observables in certain kinematic/geometrical regions, such as, the neutron/proton ratio of squeezed-out nucleons perpendicular to the reaction plane[11], are promising in reducing effects of the final state interaction, ideally one would like to have more clean ways to study the symmetry energy especially at supranormal densities. In this regard, it is interesting to note that the parity-violating electron scattering has been proposed to measure more precisely the size of the neutron-skin in ^{208}Pb [12]. The latter measured previously in experiments using hadronic probes was shown recently in several calculations to be proportional to the slope of the symmetry energy at and/or slightly below the normal density[2, 13, 14, 15, 16, 17, 18, 19]. Since only electromagnetic interactions are involved in electron scatterings the proposed experiment PREX is theoretically the most clean probe known so far for probing the low den-

sity behavior of the symmetry energy[20, 21]. However, practically it is very challenging since the probability of obtaining parity-violating electron scattering events in the experiment is extremely small. The long waited data is hopefully coming soon. Similar to electrons, photons interact with nucleons only electromagnetically. Once produced they escape almost freely from the nuclear environment in nuclear reactions. We notice that soft photons from giant dipole resonances in heavy-ion reactions have been shown within a semiclassical molecular dynamics model to be quite sensitive to the symmetry potential term in the nucleon-nucleon interaction[22]. Can one use hard photons from intermediate energy heavy-ion reactions to extract information about the $E_{\text{sym}}(\rho)$ especially at supranormal densities? This is a question that one of the present authors was repeatedly asked recently by several experimentalists on several occasions[23]. To answer this important question, we report here results of the first exploratory study on using hard photons from neutron-proton bremsstrahlung in intermediate energy heavy-ion reactions as a probe of the $E_{\text{sym}}(\rho)$.

Hard photon production in heavy-ion reactions at beam energies between about 10 and 200 MeV/A had been extensively studied both experimentally and theoretically during the last two decades, see, e.g., refs.[24, 25, 26] for a comprehensive review. Indeed, very interesting physics has been obtained from analyzing data taken by several experimental collaborations. For instance, the TAPS collaboration carried out a series of comprehensive measurements at various experimental facilities (GSI, GANIL, KVI) studying in detail the properties (energy spectra, angular distributions, total photon multiplicities di-photon correlation functions, etc), of hard photons in a large variety of nucleus-nucleus systems in the range of energies spanning $E_{\text{lab}} \approx 20 - 200$ MeV/nucleon[27]. They used those bremsstrahlung photons as a tool to

study the nuclear caloric curve, the dynamics of nucleon-nucleon interactions, as well as the time-evolution of the reaction process before nuclear break-up[28]. Theoretically, it was concluded that the neutron-proton bremsstrahlung in the early stage of the reaction are the main source of high energy γ rays. Within the cascade and Boltzmann-Uehling-Uhlenbeck (BUU) transport models it was demonstrated clearly that the hard photons can be used to probe the reaction dynamics leading to the formation of dense matter[29, 30, 31, 32, 33]. However, effects of the nuclear Equation of State (EOS) on the hard photon production was found small[34]. While these reaction models were able to reproduce all qualitative features of the experimental data, normally the quantitative agreement is within about a factor of 2. One of the major uncertainties is the input elementary $pn \rightarrow pn\gamma$ probability p_γ which is still rather model dependent[35, 36, 37, 38, 39]. It was noticed earlier that the few existing data for the $pn \rightarrow pn\gamma$ process can be described reasonably well by the available models usually within a factor of 2[26]. Looking forward enthusiastically, we mention here that the very recent systematic measurements of the $pn \rightarrow pn\gamma$ cross sections with neutron beams up to 700 MeV at Los Alamos have the potential to improve the situation significantly in the near future[40].

Since the photon production probability is so small, i.e., only one in roughly a thousand nucleon-nucleon collisions produces a photon, a perturbative approach has been used in all dynamical calculations of photon production in heavy-ion reactions at intermediate energies[24, 26]. In this approach, one calculates the photon production as a probability at each proton-neutron collision and then sum over all such collisions over the entire history of the reaction. As discussed in detail earlier in ref.[26], the cross section for neutron-proton bremsstrahlung in the long-wavelength limit separates into a product of the elastic np scattering cross section and a γ -production probability. The probability is often taken from the semiclassical hard sphere collision model[24, 25, 26]. The double differential probability, ignoring the Pauli exclusion in the final state, is given by

$$\begin{aligned} \frac{d^2 N}{d\varepsilon_\gamma d\Omega_\gamma} &= \frac{e^2}{12\pi^2 \hbar c} \times \frac{1}{\varepsilon_\gamma} (3 \sin^2 \theta_\gamma \beta_i^2 + 2\beta_f^2) \\ &= 6.16 \times 10^{-5} \times \frac{1}{\varepsilon_\gamma} (3 \sin^2 \theta_\gamma \beta_i^2 + 2\beta_f^2), \end{aligned} \quad (1)$$

where θ_γ is the angle between the incident proton direction and the emission direction of photon; and β_i and β_f are the initial and final velocities of the proton in the proton-neutron center of mass frame. The above equation was obtained from modifying the original semiclassical Jackson formula[41] to allow for energy conservation in the γ -production process[31, 32]. Integrating Eq. (1) over the photon emission angle, one obtains the single differential probability

$$p_\gamma^a \equiv \frac{dN}{d\varepsilon_\gamma} = 1.55 \times 10^{-3} \times \frac{1}{\varepsilon_\gamma} (\beta_i^2 + \beta_f^2). \quad (2)$$

We notice that other expressions derived theoretically involving more quantum-mechanical effects exist in the literature, see, e.g., [35, 36, 37, 38, 39]. Without passing any judgement on these theories, to simply evaluate influences of the elementary $pn \rightarrow pn\gamma$ probability on photon production in heavy-ion reactions, for a comparison we thus also use the prediction of the one boson exchange model by Gan et al.[38]

$$p_\gamma^b \equiv \frac{dN}{d\varepsilon_\gamma} = 2.1 \times 10^{-6} \frac{(1-y^2)^\alpha}{y}, \quad (3)$$

where $y = \varepsilon_\gamma/E_{max}$, $\alpha = 0.7319 - 0.5898\beta_i$, and E_{max} is the energy available in the center of mass of the colliding proton-neutron pairs.

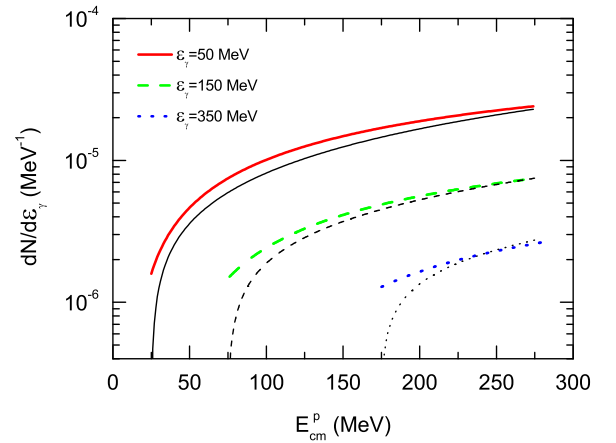


FIG. 1: (Color online) The single differential probability as a function of proton kinetic energy in the proton-neutron center of mass frame for the production of photons at energies of 50, 150 and 350 MeV, respectively. The lines with higher values are results calculated with the semi-classical Eq. (2) while the ones with lower values are obtained by using the quantum-mechanical Eq. (3).

The single differential probability p_γ^a and p_γ^b from the two models are shown in Fig. 1 as a function of proton kinetic energy in the proton-neutron center of mass frame for the production of photons at energies of 50, 150 and 350 MeV, respectively. It is seen that the two models give quite similar but quantitatively different results especially near the kinematic limit where the p_γ^a is significantly higher than the p_γ^b , as noticed already in ref.[38]. Moreover, the very small magnitude of the photon production probability shown here justifies the use of the perturbation method.

In most of the previous calculations for hard photon production using transport models, a constant nucleon-nucleon cross section of 30mb to 40mb was normally used[30, 31, 32, 34]. In this study, we use the IBUU04 transport model[42] where an isospin-dependent

in-medium nucleon-nucleon (NN) cross section

$$\sigma_{NN}^{medium} = \sigma_{NN}^{free} \left(\frac{\mu_{NN}^*}{\mu_{NN}} \right)^2 \quad (4)$$

was implemented[8]. In the above, the μ_{NN}^* and μ_{NN} are the in-medium and free-space reduced NN mass. Because of the neutron-proton effective mass splitting due to the momentum dependence of the isovector potential, the scaling factor $(\frac{\mu_{NN}^*}{\mu_{NN}})^2$ induces a significant modification to the relative cross sections of np , nn and pp as discussed in detail in ref.[8]. The energy and isospin dependent free-space NN cross section σ_{NN}^{free} are taken from the experimental data.

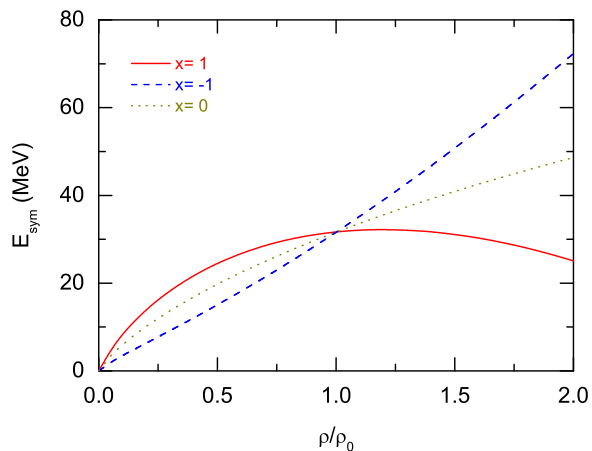


FIG. 2: (Color online) Density dependent nuclear symmetry energy.

Another important input to the transport model is the mean field. In the IBUU04 we use the momentum- and isospin-dependent single nucleon potential (MDI) given in ref.[43]. In this interaction a parameter x was introduced to vary the density dependence of the nuclear symmetry energy while keeping other properties of the EOS fixed. Fig. 2 shows the density dependent symmetry energy with $x = 1$, $x = 0$ and $x = -1$. Available experimental data on isospin diffusion[6] and isoscaling[9] have allowed us to constrain the symmetry energy to be between the curves with $x = 0$ and $x = -1$ at subsaturation densities[7, 8]. At high densities, however, there is so far no experimental constraint available. One of our major motivations here is to examine whether hard photons can be used to constrain the symmetry energy at supranormal densities as we were asked by the interested experimentalists[23].

While we are not aiming at reproducing any data in this exploratory work, it is necessary to first gauge the model by comparing with the available data. Shown in Fig. 3 are the calculations with both p_γ^a and p_γ^b and the experimental data for the inclusive cross section of hard photon production in the reaction of $^{12}\text{C}+^{12}\text{C}$ [26, 44].

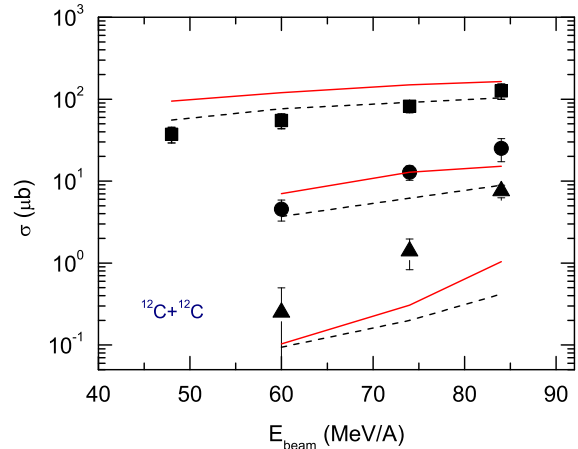


FIG. 3: (color online) Beam energy dependence of the inclusive photon production cross sections in $^{12}\text{C}+^{12}\text{C}$ collisions. The solid symbols stand for experimental data[26, 44]. (The squares are for $50 \text{ MeV} \leq \varepsilon_\gamma < 100 \text{ MeV}$, circles for $100 \text{ MeV} \leq \varepsilon_\gamma < 150 \text{ MeV}$ and triangles for $\varepsilon_\gamma \geq 150 \text{ MeV}$). The solid lines are calculated using the p_γ^a and the dashed ones using the p_γ^b .

The calculations are done with $x = 0$. It is seen that both calculations are in reasonable agreement qualitatively with the experimental data except for the very energetic photons. Quantitatively, the agreement is at about the same level as previous calculations by others in the literature[30, 32, 38]. We notice that the uncertainty in the elementary $pn \rightarrow pn\gamma$ probability leads to an appreciable effect on the inclusive γ -production in heavy-ion reactions. As one expects, the larger value of p_γ^a from the semi-classical picture gives significantly higher γ -production cross section in heavy-ion reactions. In fact, this effect is larger than the effects of the symmetry energy obtained by varying the x parameter from $x = 0$ to $x = -1$ or $x = 1$. It is thus a really very challenging task to extract useful information about the symmetry energy from photon production in heavy-ion reactions given the currently existing uncertainties associated with the elementary probability. Nevertheless, we are very hopeful that there are ways to overcome this difficulty. As an example, we will actually discuss later in this paper one possible way to do this.

We now turn to discussing effects of the symmetry energy on photon production in more detail. As an example, we consider head-on collisions of $^{132}\text{Sn}+^{124}\text{Sn}$ at an incident energy of 50 MeV/A using the symmetry energies of $x = 1$ and -1 . For this discussion, it is sufficient to use only the p_γ^b . First, we examine the evolution of the central density in Fig. 4. The highest central density reached is about $1.3\rho_0$. At this density the symmetry energy with $x = -1$ is higher by about 20% as shown in Fig. 2. The stiffer symmetry energy with $x = -1$ leads to a slightly lower central density. The supranor-

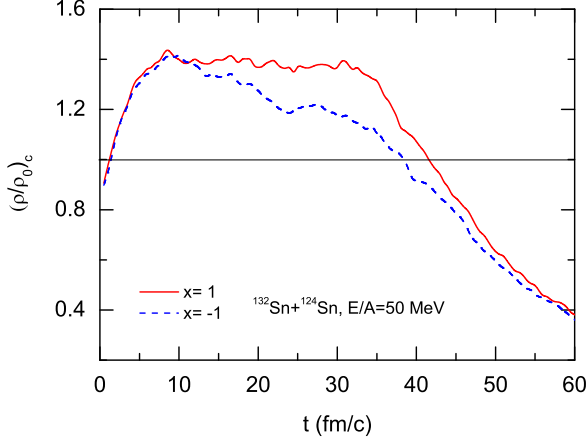


FIG. 4: (Color online) The central density reached in the head-on reactions $^{132}\text{Sn} + ^{124}\text{Sn}$ at 50 MeV/A with the symmetry energies of $x=1, -1$ using the p_γ^b . The horizontal line stands for the normal nuclear density.

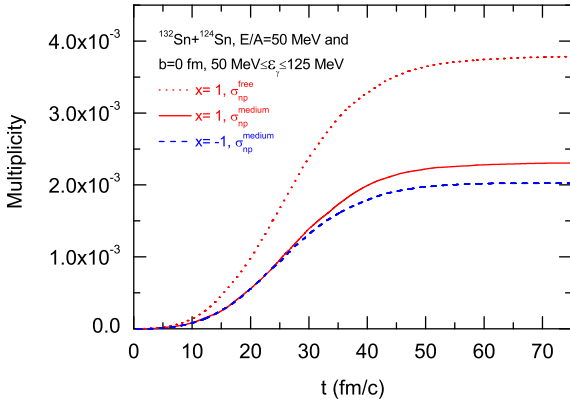


FIG. 5: (Color online) Time evolution of the multiplicity of hard photons with $50 \text{ MeV} \leq \varepsilon_\gamma \leq 125 \text{ MeV}$ in the head-on collisions of $^{132}\text{Sn} + ^{124}\text{Sn}$ at a beam energy of 50 MeV/A using the p_γ^b .

mal density phase lasts from about 10 to 35 fm/c. It is in this phase, as shown in Fig. 5, that most of the hard photons with $50 \text{ MeV} \leq \varepsilon_\gamma \leq 125 \text{ MeV}$ are produced. This observation is consistent with conclusions of the earlier studies[29, 30, 31, 32, 33]. It is seen that the softer symmetry energy with $x = 1$ produce just a little more hard photons. To investigate effects of the in-medium NN cross sections, we also carried out calculations using the free-space NN cross sections but with the same p_γ^b for the case of $x = 1$. It is seen that the free-space cross sections leads to significant higher hard photon production. This is simply because the in-medium NN cross sections are smaller than the free-space ones[8]. Moreover, we notice that the change of the NN cross sections

leads to a much larger effect than the symmetry energy. But overall, both effects are very small compared to that due to the uncertainty of the elementary γ -production probability. Nevertheless, to put the comparison into the proper context we stress that the symmetry energy and the NN cross sections are only varied, respectively, by at most 20% and 50% in the reaction considered by changing the x parameter between 1 and -1 and the cross sections between the free-space and in-medium ones. While the current uncertainty of the γ -production probability is significantly larger.

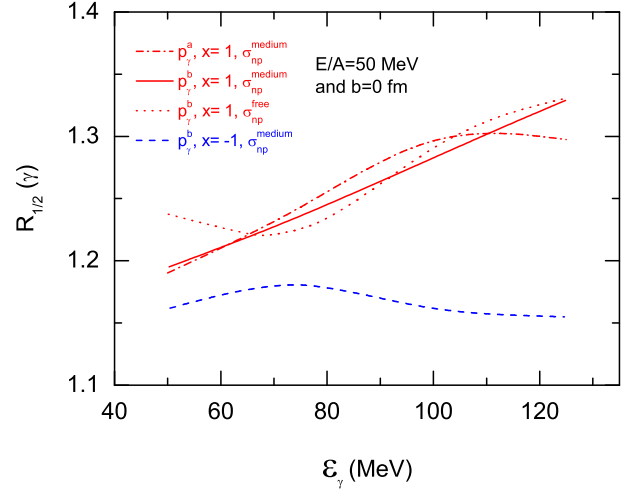


FIG. 6: (Color online) The spectra ratio of hard photons in the reactions of $^{132}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$ reactions at a beam energy of 50 MeV/A with the symmetry energies of $x=1, x=-1$.

Given all of the uncertainties discussed above and the fact that the cross section for hard photon production in intermediate energy heavy-ion collisions is very small, is there anyway one can reduce these uncertainties naturally and thus see more cleanly the effects of the symmetry energy? Like in many experiments searching for minute but interesting effects, ratios of two reactions can often reduce not only the systematic errors but also some “unwanted” effects. At least theoretically, within the perturbative approach adopted here, the uncertainty of the γ -production probability should get almost completely cancelled out in the ratio of photons from two reactions. We thus propose to measure experimentally the spectra ratio $R_{1/2}(\gamma)$ of hard photons from the head-on reactions of $^{132}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$, i.e.,

$$R_{1/2}(\gamma) \equiv \frac{\frac{dN}{d\varepsilon_\gamma}(^{132}\text{Sn} + ^{124}\text{Sn})}{\frac{dN}{d\varepsilon_\gamma}(^{112}\text{Sn} + ^{112}\text{Sn})}. \quad (5)$$

Depending on the relative number of neutron-proton scatterings in the two reactions, uncertainties due to the NN cross sections can also get significantly reduced. Shown in Fig. 6 is the $R_{1/2}(\gamma)$ calculated for four cases

using both the p_γ^a and p_γ^b . First of all, it is seen clearly that the full calculations with the p_γ^a and p_γ^b and the in-medium NN cross sections indeed lead to about the same $R_{1/2}(\gamma)$ within statistical errors as expected. It is also clearly seen that effect of the in-medium NN cross sections get almost completely cancelled out. These observations thus verify numerically the advantage of using the $R_{1/2}(\gamma)$ as a robust probe of the symmetry energy essentially free of the uncertainties associated with both the elementary photon production and the NN cross sections. Most interestingly, comparing the calculations with $x = 1$ and $x = -1$ both using the p_γ^b , it is clearly seen that the $R_{1/2}(\gamma)$ remains sensitive to the symmetry energy especially for very energetic photons. Again, the symmetry energy is varied by at most 20% in the reaction considered by varying the parameter x from 1 to -1 . Thus, the approximately 15% maximum change in the spectra ratio represents a relatively significant sensitivity. To put things in perspective, we notice that this sensitivity to the symmetry energy is actually at about the same level as most hadronic probes including the K^0/K^+ ratio. The latter using strange particles is considered as among the most clean hadronic probes of the symmetry energy[45]. It shows about a 15% change while the symmetry energy is changed by at least 50% at the density reached in heavy-ion reactions near the kaon production threshold[45]. Obviously, compared to the K^0/K^+ ratio the hard photon production is an even more sensitive and clean observable. Of course, we also notice that while photons are completely free from final state strong interactions, besides cosmic-radiation background, one needs to consider photons from π^0 and fragment decays in the data analysis[44].

Naturally, one may think about reactions at higher beam energies to reach higher densities and thus to explore the behaviors of the symmetry energy there. However, other channels for hard photon productions may start playing more important roles at higher beam energies. Moreover, the reaction dynamics will be then dominated by nucleon-nucleon collisions rather than the nuclear mean-field. Effects of the symmetry energy on photons are then expected to become smaller. This is mainly because compared to nucleons that are directly influenced by the symmetry potential, the hard photons are affected by the symmetry potential only indirectly

through the momentum distributions and the densities of the colliding proton-neutron pairs. This is also why the hard photons were found not so sensitive to the nuclear equation of state in an early study[34]. Only at intermediate energies both the mean-field and the NN collisions play about equally important roles in the reaction dynamics. In fact, we also calculated the $R_{1/2}(\gamma)$ for the same reactions but at a beam energy of 400 MeV/A. We find a much small symmetry energy effect.

In summary, we have carried out an exploratory study about effects of the symmetry energy on the production of hard photons from intermediate energy heavy-ion reactions using a perturbative approach within the IBUU04 transport model. Effects of the symmetry energy on the yields and spectra of hard photons from individual reactions are generally smaller than those due to the existing uncertainties of both the in-medium nucleon-nucleon cross sections and the elementary $pn \rightarrow pn\gamma$ probability. Very interestingly, however, the ratio of hard photon spectra $R_{1/2}(\gamma)$ from two reactions using isotopes of the same element is not only approximately independent of these uncertainties but also quite sensitive to the symmetry energy. The sensitivity is at about the same level as most hadronic probes. Compared to the K^0/K^+ ratio in heavy-ion reactions near the kaon production threshold, hard photons are completely free of final state strong interactions and are even more sensitive to the symmetry energy.

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- [1] J.M. Lattimer and M. Prakash, *Science* **304** (2004) 536.
 - [2] A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, *Phys. Rep.* **411** (2005) 325.
 - [3] B.A. Li, C.M. Ko and W. Bauer, topical review, *Int. J. of Modern Phys.* **E7** (1998) 147.
 - [4] *Isospin Physics in Heavy-Ion Collisions at Intermediate Energies*, Eds. B.A. Li and W. Udo Schröder, Nova Science Publishers, Inc (2001, New York).
 - [5] V. Baran, M. Colonna, V. Greco and M. Di Toro, *Phys. Rep.* **410** (2005) 335.
 - [6] M.B. Tsang *et al.*, *Phys. Rev. Lett.* **92** (2004) 062701.
 - [7] L.W. Chen, C.M. Ko, and B.A. Li, *Phys. Rev. Lett.* **94** (2005) 032701 [arXiv:nucl-th/0407032].
 - [8] B.A. Li and L.W. Chen, *Phys. Rev. C* **72** (2005) 064611.
 - [9] D.V. Shetty, S.J. Yennello and G.A. Souliotis, *Phys. Rev. C* **76** (2007) 024606.
 - [10] L.W. Chen, C.M. Ko, B.A. Li and G.C. Yong, *Front. Phys. China* **2** (2007) 327 [arXiv:0704.2340]; arXiv:0711.1714.
 - [11] G.C. Yong, B.A. Li and L.W. Chen, *Phys. Lett.* **B650**

- (2007) 344.
- [12] C.J. Horowitz and J. Piekarewicz, Phys. Rev. Lett **86** (2001) 5647; Phys. Rev. C **66** (2002) 055803.
 - [13] B.A. Brown, Phys. Rev. Lett. **85** (2000) 5296.
 - [14] S. Typel and B.A. Brown, Phys. Rev. C **64** (2001) 027302.
 - [15] R.J. Furnstahl, Nucl. Phys. **A706** (2002) 85.
 - [16] S. Karataglidis, K. Amos, B.A. Brown, and P.K. Deb, Phys. Rev. **C65** (2002) 044306.
 - [17] J.R. Stone *et al.*, Phys. Rev. C **68** (2003) 034324.
 - [18] A.W. Steiner and B.A. Li, Phys. Rev. C **72** (2005) 041601.
 - [19] L.W. Chen, C.M. Ko, and B.A. Li, Phys. Rev. C **72** (2005) 064309.
 - [20] R. Michaels, P.A. Souder and G.M. Urciuoli, Jefferson Laboratory Proposal PR-00-003 (2000).
 - [21] C.J. Horowitz, S.J. Pollock, P.A. Souder and R. Michaels, Phys. Rev. **C63**, 025501 (2001).
 - [22] G. Giuliani and M. Papa, phys. Rev. **C73**, 031601(R) (2006).
 - [23] A. Chbihi, G. Verde, J.P. Wieleczko et al. private communications.
 - [24] G.F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
 - [25] H. Nifenecker and J.A. Pinston, Annu. Rev. Nucl. Part. Sci. 1990. 40: 113-43.
 - [26] W. Cassing, V. Metag, U. Mosel, and K. Niita, Phys. Rep. **188** (1990) 363.
 - [27] David d'Enterria and Gines Martinez, private communications.
 - [28] Y Schutz et al. for the TAPS collaboration, Nucl. Phys. **A622**, 404-477, (1997); G. Martinez et al., Phys. Lett. **B461**, 28 (1999); David d'Enterria et al., Phys. Lett. **B538**, 27 (2002); R. Ortega et al., Eur. Phys. J. **A28**, 161 (2006).
 - [29] B.A. Remington, M. Blann and G.F. Bertsch, Phys. Rev. Lett. **57** (1986) 2909.
 - [30] Che Ming Ko, G.F. Bertsch and J. Aichelin, Phys. Rev. C **31** (1985) 2324(R).
 - [31] W. Cassing, T. Biro, U. Mosel, M. Tohyama, and W. Bauer, Phys. Lett. **B181** (1986) 217.
 - [32] W. Bauer, G.F. Bertsch, W. Cassing and U. Mosel, Phys. Rev. C **34** (1986) 2127.
 - [33] J. Stevenson et al., Phys. Rev. Lett. **57** (1986) 555.
 - [34] C.M. Ko and J. Aichelin, Phys. Rev. **C35**, 1976 (1987).
 - [35] H. Nifenecker and J.P. Bondorf, Nucl. Phys. **A442** (1985) 478.
 - [36] K. Nakayama and G.F. Bertsch, Phys. Rev. **C34**, 2190 (1986).
 - [37] M. Schäffer, T.S. Biro, W. cassing and U. Mosel, H. Nifenecker and J.A. Pinstan, Z. Phys. **A339**, 391 (1991).
 - [38] N. Gan et al., Phys. Rev. C **49** (1994) 298.
 - [39] R.G.E. Timmermans, T.D. Penninga, B.F. Gibson, M.K. Liou, Phys. Rev. C **73** (2006) 034006.
 - [40] Y. Safkan et al., Phys. Rev. C **75** (2007) 031001(R).
 - [41] J.D. Jackson, Classical Electrodynamics (Wiley, New York, 1962), Ch. 14.
 - [42] B.A. Li, C.B. Das, S. Das Gupta and C. Gale, Phys. Rev. C **69** (2004) 011603(R); Nucl. Phys. **A735** (2004) 563.
 - [43] C. B. Das, S. Das Gupta, C. Gale and B.A. Li, Phys. Rev. C **67** (2003) 034611.
 - [44] E. Grosse et al., Europhys. Lett. **2**(1986)9.
 - [45] G. Ferini, T. Gaitanos, M. Colonna, M. Di Toro and H. Wolter Phys. Re. Lett. **97** (2006) 202301; V. Prassa, G. Ferini, T. Gaitanos, H.H. Wolter, G.A. Lalazissis and M. Di Toro, Nucl. Phys. **A789**, 311 (2007).